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Experimental Study of Impinging Jet Flow-Fields

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Section I: Project Summary

1. Overview of Project

This project focused on experiments to improve the understanding and aid in the analysis of Short Take-Off and Vertical Landing (*STOVL*) vehicle aerodynamics during sea-based operations. The overall goal of the research was to conduct experiments to define the major features of complex dual impinging jet flow-fields. Also, a major objective was to guide numerical simulation developments and provide a database to thoroughly evaluate the accuracy of these predictions. This research is integrated strongly with numerical simulations of the time mean and unsteady features of the dual impinging jet flow-fields being conducted primarily by colleagues at the Applied Aerodynamics and Store Separation Branch (AIR 4.3.2.1) of the Naval Air Warfare Center-Aircraft Division, at Patuxent River, MD. The current laboratory model consists of dual jets impinging on a large flat plane in order to simulate the jets that provide powered lift for *STOVL* aircraft in hover. The nozzles are mounted in a simplified aircraft underside, or lift plate. An open jet wind tunnel is currently used to represent environmental winds from the direction directly upstream of the simplified model. A pitot pressure rake has been used for numerous mean velocity surveys of the jet plumes and outwash flow. Lift plate surface pressure measurements have also been made. The unsteady flow, known to have significant large scale resonances, was characterized through shadowgraph visualization. Unsteady single point Laser Doppler Velocimeter (LDV) measurements were conducted to determine turbulence statistics throughout the flow-field and to quantify the jet column resonances. The initial portion of the current project contributed to the identification and measurement of the major features of the flow-field generated by the two parallel impinging model jets. These accomplishments are summarized in the first part of this final report.

At the conclusion of the initial unheated impingement jet measurements, our group received strong encouragement from our Navy Point of Contact, Dr. David Findlay, to consider giving a high priority to actual heated jet measurements. In shipboard operations, modern *STOVL* aircraft produce new problems for ships' crews and equipment. The high velocities and temperatures require restricted occupancy regions that constrain efficient shipboard operations. Navy plans to develop reliable computer simulations of the shipboard environments of hovering and landing of *STOVL* aircraft would help with crew training and improved safety for such operations. These simulations require the prediction of heat transfer phenomena as well as the aerodynamics of the high-temperature, high-speed flow-fields. Experiments described here in our laboratory are contributing to this goal with physical understanding and data to evaluate the predictive capability of the numerical simulations.

During the second (and final) year of the project a major upgrade to our laboratory model was completed in preparation for the heated jet experiments. This included the addition of a jet heating capability together with insulated high temperature delivery piping to the model exhaust jet. In addition, a large number of thermocouples positioned at strategic positions throughout the apparatus were installed. During preparations for the experiments to be conducted with the dual impinging jet model (with one heated jet), discussions were conducted with the NAWC Organization, specifically Dr. Andrew Crowell (AIR 4.3.2.1), who was working on the development of numerical simulations to predict the aero-thermo-dynamics of fixed wing *STOVL* aircraft in ground effect. He had initially undertaken some unsteady RANS computations of the flow-field based on the Penn State dual impinging jet model in the absence of any jet heating. The results of the computations had been compared with the experimental data produced in the recently completed Penn State PhD dissertation of Leighton Myers, who also co-authored an AIAA Paper with Dr. Crowell (Refs. 1 and 2). Dr. Myers has since joined the AIR 4.3.2.1 Branch at NAWC. As part of Dr. Crowell's initial efforts to include the analysis of heated impinging jets, he performed RANS computations of a single hot jet impinging on two smooth surfaces with different heat transfer characteristics. The two teams coordinated the geometry and jet operating conditions of the computations to conform to conditions planned for some of the first heated jet experiments at Penn State.

The conditions selected by Dr. Crowell for his CFD computations, which included heat transfer, fit very well with the initial experiments underway at Penn State. The outputs obtained from the CFD computations were ideal for the Penn State team to use in finite difference heat transfer calculations of the heat flow and temperature distributions that are created in the ground plane used in the experiments (Ref. 3). The results of both of these sets of computations are summarized in the following sections. Additionally, for one of the geometry and jet conditions, measured temperature distributions were compared with those predicted from the coupled CFD-conjugate heat transfer calculations.

2. Summary of Activities throughout the Grant period

2.1 Experiments with Generation 1 Model

The first dual impinging jet model built at Penn State (referred to as Generation 1) was designed to produce proof-of-principle measurements to show the capabilities of our facility and measurement techniques. The first model jets had no heating capability, so that the focus was on the aerodynamic measurements. All measurements were successfully completed to the point that extensive comparisons with the CFD calculations performed by the AIR 4.3.2.1 Branch at NAWC were documented. Figures 1 and 2 show the Generation 1 dual impinging jet model used for aerodynamic measurements that included pitot rake and Laser Doppler Velocimeter, (LDV*)* surveys of the jet plumes, impingement regions, and outwash flow.

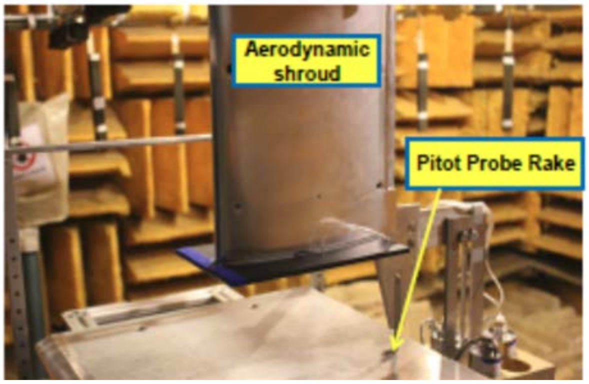


Figure 1. Photo of the dual impinging jet model in the open jet anechoic wind tunnel.

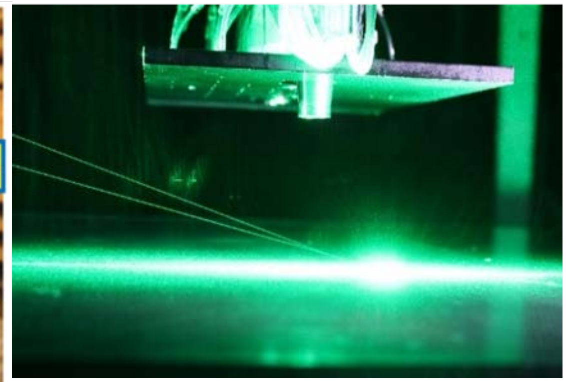


Figure 2. Close up of the LDV measurement volume in the impingement region of the supersonic jet.

Laser Doppler Velocimeter Measurements

Highlights of the LDV measurements are presented in the next two figures. Figure 3 a) includes velocity contours interpolated from the LDV data measured in a jet of exit Mach number *Ma*=1.34 positioned 12 jet exit diameters above the ground plane. Part a) of Figure 3 shows the velocity data measured with the LDV, first in the portion of the jet that is relatively undisturbed by the ground plane. The lower portion, b) of Figure 3 includes contours from LDV measurements in the very near wall impingement region of the jet. For these measurements the jet stand-off distance was 6 jet diameters. In order to better understand the effect of the ground plane on the mean flow features and turbulence characteristics of the supersonic jet plume, mean velocity profiles and turbulence intensities were measured for several lift plate to ground plane separations.

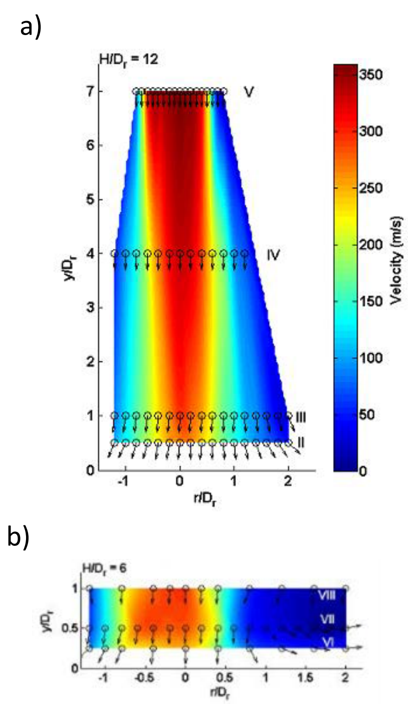
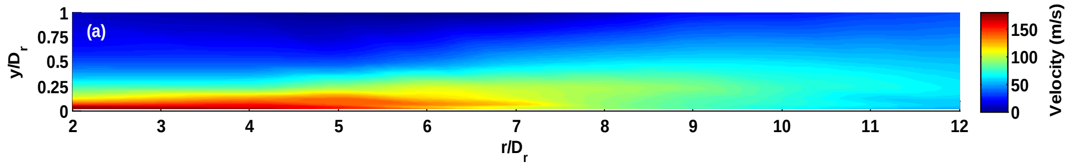
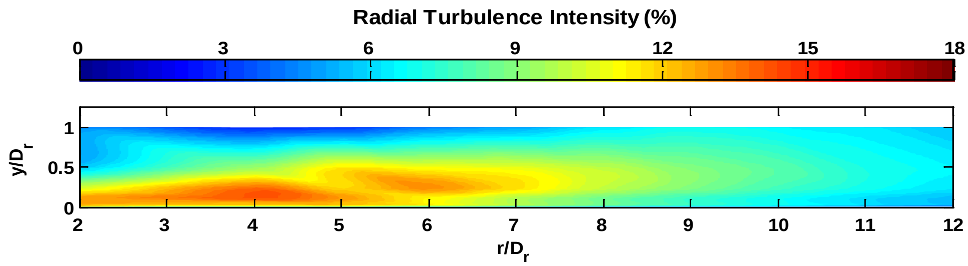


Figure 3 LDV Velocity measurements in the impinging jet.

The radially directed wall jet is one of the major safety hazards on board ships from which *STOVL* aircraft operate. Figure 4 shows contours of radial velocity measured with the five probe pitot rake (Figure 4a) and the turbulence intensities measured with the LDV (Fig. 4b) in the outwash flow. An aspect of the turbulence in the impinging jet flow fields is the **impingement resonance** that can occur in the model flow-field being measured. This resonance, or impingement tone is observed in both the acoustic field and unsteady LDV flow measurements when the jet exhaust nozzles are within 10 diameters of the impingement plate. The frequency of this tone varies inversely with the jet standoff distance.



a). Radial wall jet Mach number measurements with 5 probe pitot rake



b) Radial wall jet turbulence intensities; measured with LDV.

Figure 4. Mean and unsteady wall jet measurements; nozzle exit velocity of 380*m/s*.

A difficult aspect of the measurement of accurate frequency spectra from LDV data is that the individual particle measurements with the LDV are at unequal time intervals, corresponding to the random particle arrival times. Our data processing has shown an ability to account for the uneven arrival times and produce spectra including estimates of the impingement tones as a function of jet standoff distance and jet velocity. The accuracy of the LDV to measure this frequency was established by direct comparison with near field acoustic measurements. Figure 5 is an example of the velocity data measured in an impinging jet in our laboratory. Note that the peak in the velocity spectrum at about 12.7 kHz precisely matches the peak in the near-field acoustic spectrum (in red). It is anticipated that these types of measurements can make up a database that will be particularly useful in validating the CFD code predictions that result from the numerical simulation work. The results of these experiments are discussed in more detail in the conference papers listed as Refs. 4 - 6.

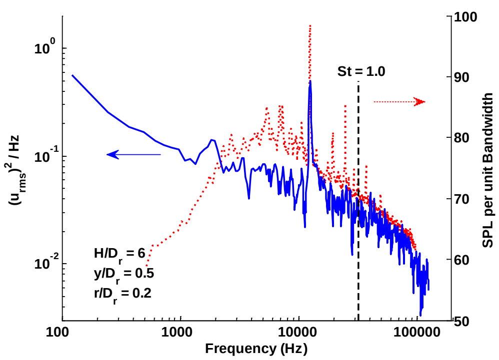


Figure 5. Far-field acoutic spectra (red) and velocity spectra (blue) obtained via unsteady LDV measurements.

2.2 Facility Upgrades in Preparation for Upcoming Heated Jet Experiments.

A major portion of the activity during the first half of our second project year was focused on bringing to readiness the heated jet capability of the dual impinging jet model. The overall system design is shown in the CAD rendering in Figure 6 emphasizing the **hot jet delivery** line. The two heaters are located on the roof of the anechoic chamber, a position chosen to minimize the length of the hot portions of the delivery line (which are subject to thermal expansion during operation). All hot jet lines are high temperature stainless steel and well insulated for safety reasons and to insure that the delivered air is at a uniform temperature within a reasonable tolerance. A 70 psi pop-valve is used to prevent over-pressurization of the heaters, and a bellows component compensates for thermal expansion in the high-temperature supply line. Figure 7 shows a *CAD* rendering of the **upgraded dual jet model** showing the delivery piping and structural components before the addition of thermal insulation, pressure tap leads and the outer fairing (which decreases the disruption of the simulated headwind provided by the open jet of the wind tunnel).

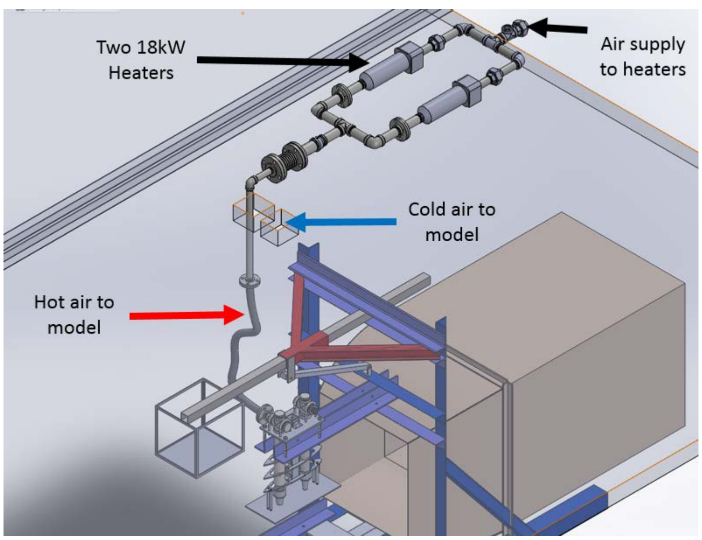


Figure 6. *CAD* rendering of the arrangement planned for the two heaters in the hot jet delivery.

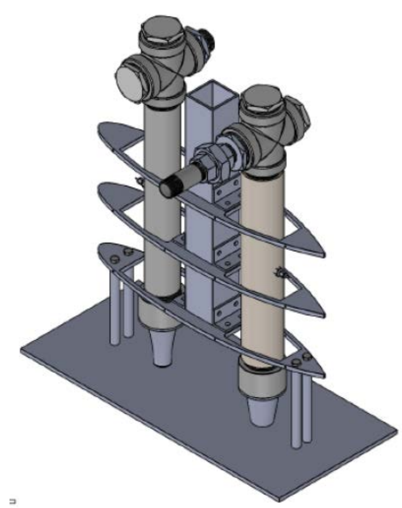


Figure 7. *CAD* Rendering of the internal components of the Generation 2 model.

The generation 2 model refers to the model designed and fabricated during this past year to specifically accommodate hot flows to the rear jet. The piping leading to the rear jet has room to fit ceramic cylindrical components over the hot stainless steel delivery lines. Additionally high temperature thermal insulation is added between the hot piping and the external fairing to protect the other internal components from the heat.

The **design of the ground plane** has been based on several factors, the most important of which is the plans that have previously been developed for the impinging jet simulation code that includes heat transfer to the ground plane. Initial efforts for the numerical simulation were directed toward determining the accuracy of the unsteady RANS CFD code to compute the complicated flow-field that includes compressible (sometimes supersonic) flow with turbulence components that did not have well established models with proven acceptable accuracy. This objective was met to a large measure by the previous work of Dr. Crowell (computations) and Dr. Myers (in PhD experiments at Penn State). Next came the consideration of the accuracy of the numerical simulation to also predict the heat transfer to the ground below the high velocity, highly turbulent flow-field. In this conjugate heat transfer problem, the heat transfer distribution is strongly dependent on the temperature of the surface of the ground plane, which in turn is dependent on the geometry and material properties of the ground plane. These properties determine the heat flow within the ground plane.

For initial heat transfer analyses, the geometry of the ground plane was chosen to be as simple as possible. Thus the ground plane was specified to be uniformly flat and of constant thickness with material properties able to withstand the temperature of the hot jet. The exterior dimensions were chosen to be at least 50 times the diameter of the hot jet, so that the furthest dimensions would exceed those of interest in practical aircraft applications. Also, the temperatures and velocities at the furthest distances would be at least an order of magnitude lower than the initial hot jet temperature and velocity. The simplest analysis included insulated surfaces on the bottom and (effectively) the edges of the ground surface. Figure 8 shows a schematic diagram of the ground plane geometry that was duplicated in both the numerical simulations and the experiments.

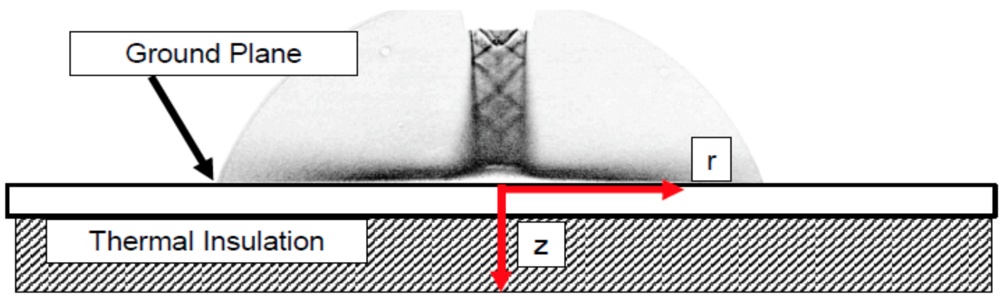


Figure 8. Concept design of ground plane

The heat transfer process of the high velocity hot jet impinging on the level flat plate depends strongly on the distribution of the heat (the thermal energy) from the top surface down into the ground plate and radially away from the impingement region of the jet. To provide an effective manner to evaluate the prediction of this heat transfer process, ground planes of two relatively thin aluminum plates were chosen: 0.635 and 3.175 mm thick. As expected, during the initial exposure of the plate to the hot jet, the thin plate temperature response occurred approximately 5 times faster than the thicker plate. Temperature response data will be presented in a later section of this report.

The ground plane consists of two components; a thin, instrumented plate and a frame surrounding the perimeter of the instrumented plate. The instrumented portion of the plate is constructed using a 61 *cm* x *43 cm* sheet of aluminum plate. Two adjacent edges of this plate remain stationary, and are attached to the corresponding edges located on the frame surrounding the perimeter. The remaining two adjacent edges use a tensioning mechanism and slip-joint construction to allow for the displacement of the edges. This construction allows the **instrumented plate to be pre-tensioned**, reducing the effects of thermal expansion and surface deformations due to high temperatures during jet impingement. The frame surrounding the perimeter of the instrumented plate increased the overall dimensions of the plate to 91 *cm* x *74 cm*. The plate and frame assembly were attached to a larger, *91 cm* x 91 *cm* x 4.76 *mm*, structural plate with 31 *mm* aluminum spacers.

The 0.635 mm thick ground plane was instrumented with a total of forty type K thermocouples on the lower surface of the ground plane. Because the 0.635 mm thick ground plane has a very rapid response to the hot impingement jet, transient temperature measurements require very fast response instrumentation, beyond the capability of the available thermocouples. For this reason this ground plane was predominantly used for steady-state measurements. The thermocouples measure the changes in temperature distribution on the lower surface of the ground plane. The difference between the upper and lower surface temperatures is easily predicted using basic heat transfer analysis. A photograph of the thermocouples attached to the ground plane is shown in Figure 9, and the installed view in Figure 10 shows the thermocouple output leads.

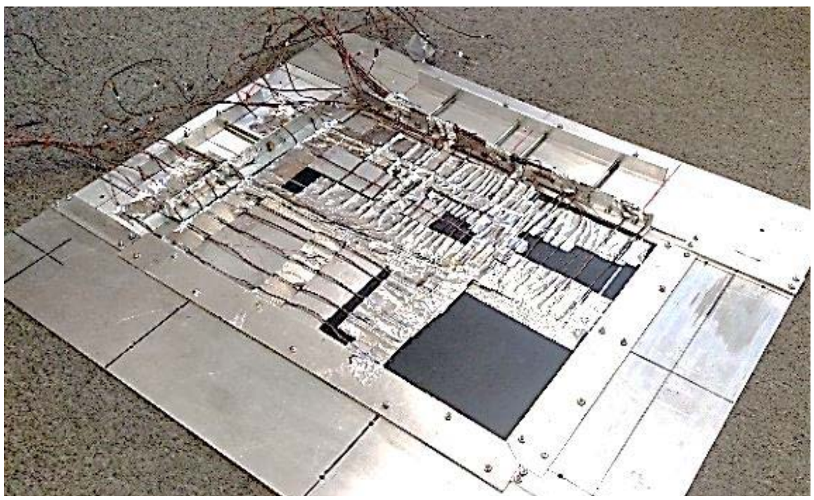


Figure 9. Photograph of underside of ground plane with attached thermocouples.

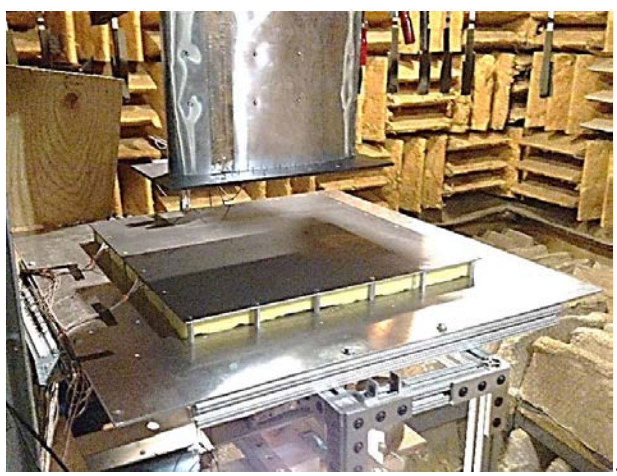


Fig. 10. Photograph of the first thermocouple instrumented ground plane installed in the anechoic chamber.

Beneath the instrumented plate, a 61 *cm* x 43 *cm* x 31.8 *mm* panel of rigid mineral wool insulates the lower surface. Figure 10 shows the complete ground plane assembly installed in the anechoic chamber (with the thermocouple leads shown on the far left of the photograph).

2.3 Coordination with CFD and Ground Plane Heat Transfer Calculations.

To aid in the design of the initial heat transfer experiments, Dr. Andrew Crowell of AIR 4.3.2.1 Branch at NAWC completed initial CFD computations of a single hot impinging jet. The jet was positioned 6 jet diameters above the ground plane. Using a nozzle pressure ratio of NPR = 2.3 produced a Mach number 1.2 jet and the total temperature ratio TTR of 1.5 gave a jet of exit total temperature of 435 K for an ambient condition of 290 K. The computations were performed in dimensional units in which the jet exit diameter was D_j = 13 mm (1/2 inch). The initial CFD RANS computations were performed with an isothermal wall boundary condition at the ambient temperature of 290 K. This could represent a situation in which the wall was held at a constant temperature by an active (powerful) cooling system. The second computation was performed assuming the wall had been allowed to rise in temperature to the level, at each radius, equal to the adiabatic wall temperature of the flow. Both of these wall surface temperature distributions are plotted in Figure 11a. For the computations performed at constant wall temperature the heat transfer flux can be computed from the slope of the vertical temperature profile at the wall. This resulting heat flux distribution is plotted in Figure 11b.

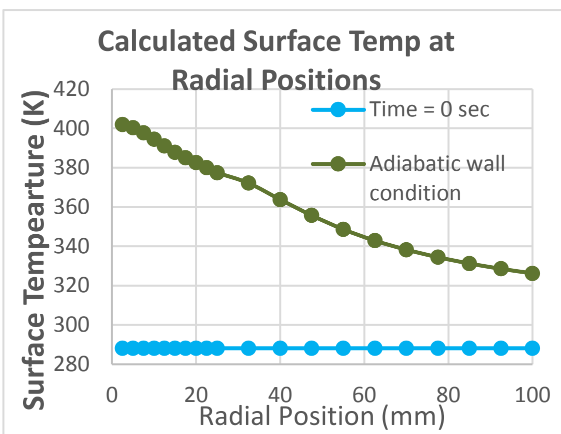


Figure 11a. Surface temperature determined from RANS CFD computations for adiabatic and constant cold wall temperature surface boundary conditions.

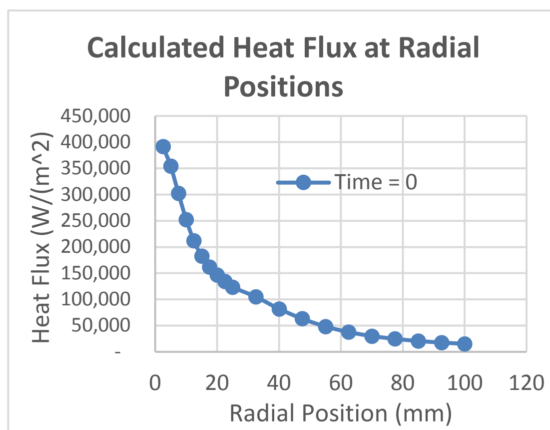


Figure 11b. Computed heat flux corresponding to the single hot jet impinging on a constant temperature (T ambient) lower surface.

Comparison of the first ground plane temperature measurements with predictions

The first measurements presented are for the ***steady state condition*** with the thermocouple array for comparison with the adiabatic condition obtained from the CFD computations of Dr. Crowell. A temperature distribution result of our initial (heated jet) experiments with the test CFD computations for the *NPR* =2.3, *TTR* = 1.5 hot jet with a standoff distance of 6 jet diameters is shown in Figure 8a. The continuous red curve is the adiabatic wall temperature predicted from the CFD computation for the jet conditions listed above. The solid symbols are the temperature measurements made on the underside of the relatively thin plate after steady state conditions were established. The very close agreement between prediction and experiment provides strong evidence of the validity of the computations, and also of the experimental approach.

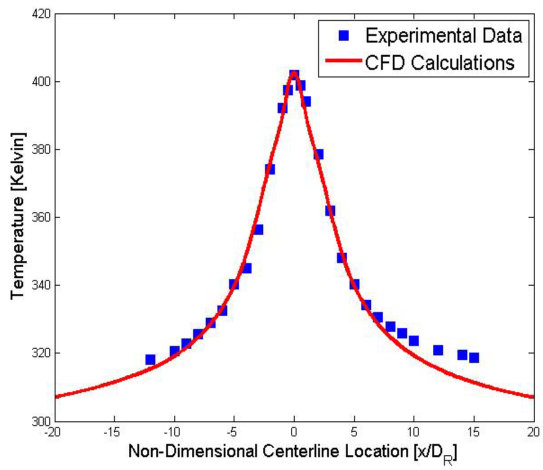


Figure 12a. Initial single heated jet experiment; thermocouple measurements of the ground plane temperature distribution.

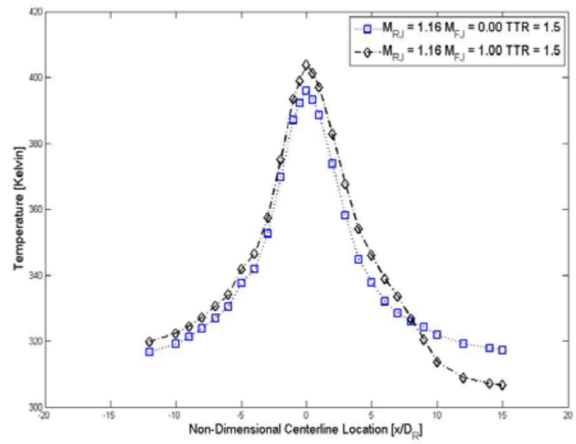


Figure 12b. Dual impinging jet experiment; measurements of the ground plane temperature distributions with the cold jet off and then on.

In Figure 12b are plotted two measured temperature distributions, both with the same hot jet operating and stand-off conditions but also contrasting the conditions in which the forward unheated jet is first turned off and then turned on. Note that the data on the right of the plot in Figure 12b, is the region between the two jets. The intrusion of the cold air is showing its influence on the ground plane temperature. These most recent data will be compared with adiabatic wall CFD computations to be undertaken in the future (in collaboration with NAWC colleagues). The data produced from these heat transfer experiments and more details of the technical approach are discussed in Refs. 7 and 8.

Transient Analysis and Experiment

The major goal of NADC is to develop the computational simulation of the flow-field and heat transfer processes involved in the initial hover and vertical landing of a simplified model of the F-35B aircraft onto the confined area of a portion of the deck of a Navy ship. During the landing process as the aircraft descends, the flow field involving the two main impinging jets is constantly changing. An accurate numerical simulator will need to compute the complex flow-field as well as the heat transfer into the ground plane slab at several intervals of time (or descent heights). These will be fully conjugate heat transfer calculations. It could be assumed that the rate of change of that flow-field with aircraft descent will be on a slower time scale than will the rates of change of the surface temperature of the ground plane or of the adjustment of the turbulent flow to either surface temperature or aircraft stand-off distance. Hence, the present study concentrated on the time evolution of the physics of the medium time scale processes, namely the calculation of the temperature distribution within the ground slab for a constant jet stand-off distance and constant jet exit flow. The CFD calculations performed with a single constant property hot jet matches those established for the initial Penn State experiments. The initial computations by Dr. Crowell are for a ground plane of constant ambient temperature (Ref. 2). The heat transfer rates are very high and a heat transfer analysis predicts a very rapid rise in the ground plane temperature. It is known, however, that the high heat transfer rates will not be sustained as the local surface temperatures rise and the potential for convective heat transfer is correspondingly decreased. The model, developed at Penn State, can adjust for this decreased thermal potential as described in the following paragraphs.

The model to be described is an inner-loop of a fully conjugate heat transfer computation, which would also involve recalculations of the outer CFD flow-field (particularly as the jet stand-off distance decreased). It is for this reason that the current method is a finite difference calculation of the conduction heat transfer in the ground plane plate (or slab) subject to specified heat transfer rates at the upper surface. The surface boundary condition is determined from the CFD computation of the flow-field of the impinging jet(s). This inner-loop computes the change in the temperature distribution in the radial direction and the direction perpendicular to the surface of the ground plane (that is subjected to the rate of heat transfer specified at the first time step of the CFD computation). During the inner loop of the computations, the conditions of the outer CFD flow-field are held constant in time at each (radial) position as is the surface heat flux distribution. The most important result of each inner-loop calculation is an updated temperature field of the ground slab, specifically, the surface temperature distribution. For each subsequent time step, the ground plane temperature field is calculated with an updated heat transfer flux distribution, calculated using Newton's Law of Cooling (using the updated surface temperature of the ground plane from the previous time step). The plot of these predicted temperature distributions is shown in Figure 13. The impinging jet flow adiabatic wall temperature as a function of radius, $T_{aw}(r)$, remains constant in time leading to a smaller differential temperature between the flow and the plate for each subsequent iteration. This adiabatic wall temperature is also referred to as the recovery temperature of an oncoming boundary layer flow.

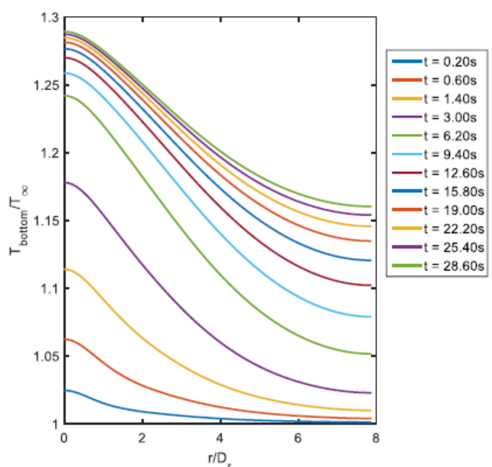


Figure 13. Zonal surface temperature from the transient model of the 3.175 mm thick ground plane.

It is noted that at a time of 28 sec the temperature profile is similar to the adiabatic wall temperature distribution presented earlier in Figure 12a but not precisely the same. The adiabatic boundary condition at the surface matches experiment with CFD computation but significant energy transfer in the radial direction within the ground plate is not accounted for in the adiabatic CFD calculation.

Experiments similar to those that produced the data shown in Figure 12 were conducted with the thicker (3.125 mm) ground plane. This plate, being five times thicker, has time scales that are also approximately five times longer and provide an opportunity for the thermocouple instrumentation to adequately resolve the changing surface temperature. In this case the conduction heat transfer computation is determining the bottom surface temperature to match the location of the thermocouples.

From this comparison, it is noted that the family of experimental and computational data match the shapes of the curves quite well but the numerical values have a significant mismatch. In the outwash region, the computational model matches experimental data for small time increments, but as the time increases, the difference in the outwash region increases.

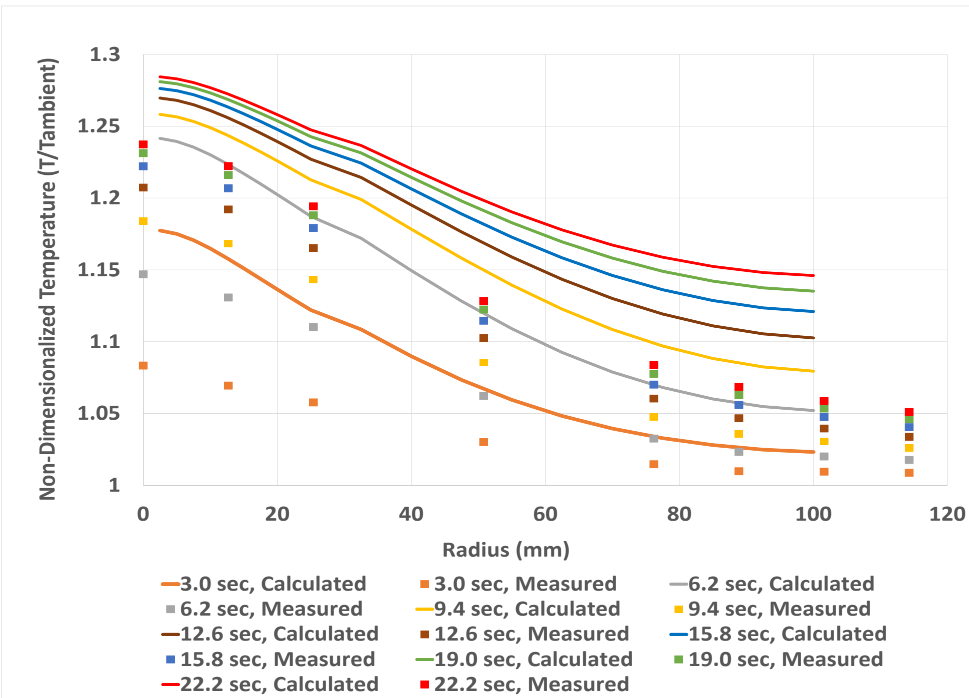


Figure 14. Comparison of conduction computational model of evolving surface temperature to measurements in the ground plane of the impinging jet model for jet conditions M_{RJ} = 1.16 and TTR_{RJ} = 1.5 at a separation distance H/D_R = 6.

It is possible that the source of the difference noted could be attributed to time lags in the thermocouple measurements. Alternatively, the plate size used in the computational model (a circular plate with a diameter of 200 mm) was used to reduce the problem of inadequate memory on the personal computer used for the heat transfer calculations. This size is approximately one-half of the size of the ground plate used in the experiment. Since the edge conditions for the computations assumed adiabatic conditions, this would curtail the radial heat transfer to larger diameters which would result in excess temperatures in the smaller computational domain.

At present the activities described above were the last experiments conducted at the expiration of our funding. Continuing work in this area will require some level of funding beyond what has been secured to date.

References

1). Myers, L.M., "Investigation of the Flow-Field of Two Parallel Round Jets Impinging Normal to a Flat Surface", PhD Dissertation, Penn State University, August 2015.

2). Crowell, A. and Myers, L. M., "Experimental Comparison of Model Scale Impinging Jets," in *54th AIAA Aerospace Meeting*, January 2016, AIAA Paper # 2016-0310, San-Diego, California, pp. 1–21.

3). Zuk, J. "Development of a Transient Conduction Heat Transfer Computational Model to use with a Quasi-Steady CFD Analysis of a Heated Jet Flow Impinging on a Level Ground Plane", Masters paper, Penn State University, June 2016.

4). Myers, L.M. and McLaughlin, D.K., "Outwash Measurements of a Dual Impinging Jet Scale Model," AIAA 2015-1937, presented at the AIAA Sci-Tech Conference, Kissimmee, Florida, Jan, 2015.

5). Hromisin, S., Rudenko, N., Myers, L. and McLaughlin, D.K. "Laser Doppler Velocimeter Measurements in the Ground Interaction Region of an Impinging Scale Model Jet," in AHS 71st Annual Forum, Virginia Beach, VA. 2015.

6). Hromisin, S., Myers, L.M., McLaughlin, D.K. and Morris, P.J. "A Comparison of the Aeroacoustic Characteristics of Free and Impinging Jets with Deflected Seals Noise Reduction Technique", AIAA Paper # 2016-0526, Aerospace Sciences Meet., San Diego, CA., Jan. 2016.

7). Rudenko, N.A., " Investigation of the Heat Transfer of two Jets Impinging Normal to a Flat Surface" MS Thesis, Penn State University, August, 2016.

8). Rudenko, N.A., Hromisin, S.M. and McLaughlin, D.K., "Thermal Characterization of a Dual Impinging Jet Flow Field with a Heated Jet", Presented at the AIAA Aviation Meeting, Washington, DC, June 2016

3. Significance of Results

The current effort contributes to the need for innovative experimental and computational methodologies for the prediction and analysis of *STOVL* vehicle aerodynamics in hover. The specific flow-fields that are studied involve multiple impinging jets that are similar to those that provide the powered lift for *STOVL* aircraft. At full-scale these flow-fields contain multiple jet mixing, outwash, aircraft suck-down effects, and re-ingestion (of hot exhaust gas into the region of engine inlets). The experiments and analysis underway at Penn State have been strongly coupled with numerical simulation work underway in the Aerodynamics and Store Separation Branch at NAWC, Patuxent River, Maryland.

4. Plans for a possible Grant extension

The funds committed for this project have been fully expended. Should funds be made available beyond the current Grant, the following paragraphs summarize the activities that would be undertaken.

1) Additional conduction heat transfer computations will be conducted with a computational domain set to the same size as the experiment. This should shed light on the current mismatch we have with the numerical values of the model calculations in comparison to the transient experiments.

2) A rake of closely spaced thermocouple sensors would be designed, fabricated and calibrated to work in conjunction with the current pitot probe rake to measure the velocity and temperature distributions of the wall jets that model the outflows on the deck of a ship during a STOVL aircraft landing. As with the surface temperature measurements conducted during the last quarter of the current grant, these experiments would be conducted with variations in the main operating parameters of the current model: impinging jet stand-off distance, total temperature ratio of the rear hot jet and some variations in the exit velocities of the two impinging jets (controlled by their nozzle pressure ratios).

3) Adapt a newly acquired thermal imaging camera to obtain an independent measurement of the ground plane surface temperature. Additional our department recently submitted a proposal to the DURIP program to acquire funds to purchase and assemble a new Particle Image Velocimeter system. This should enable much more extensive and accurate flow-field measurements of the mean velocity field as well as the turbulence of the dual impinging jet model. This in turn should benefit the computational developments leading to improved simulators for improved training leading to actual improved on-board ship safety

4) Instrument the lift plate that surrounds the two impinging jet nozzles, with thermocouples to obtain a measure of how much fountain flow reaches the surroundings of the jets. This will also be compared with the computational data.

5) Perform some component of the measurements made to this point, with measurements made in a similar flow including a controlled headwind. This headwind will be produced by the open jet wind tunnel; the current impinging jet model is currently located in the test section of this open jet.

6) Include a defined activity to interrogate the CFD computations that are anticipated to continue by in the Air Branch 4.3.2.1 at NAWC and by Scott Hromisin, SMART Scholar, under the mentorship of NAWC. There are many components of the CFD computations for which experimental data will be made available. Properly preparing such data will require a sizable commitment of time that should reduce the time commitment of NAWC.

5. Recommended reading

[1] Crowell, A, and Polsky, S., “Innovative Low Cost Reduced Order Predictions of the Aero-Thermo-Dynamics of V/STOL Aircraft in Ground Effect,” Independent Applied Research (IAR) Program, NAVAIR, Patuxent River, MD.

6. Transitions/Impact

As mentioned earlier, the experimental data of this study are supporting a modeling and simulation activity at NAVAIR, 4.3.2.1, who have been using Cobalt to compute RANS simulations of the PSU dual impinging jet scale model. The experimental data obtained from the current ONR program will be critical in evaluating the simulation results. The transfer of experimental data to NAVAIR for the foreseeable future.

7. Collaborations

During meetings and telephone conference calls with Dr. Leighton Myers, of NAVAIR, it is our understanding that they are beginning to develop the inclusion of heat transfer effects in their numerical simulation work on the powered lift shipboard operations. Our discussions have focused on attempts to maintain consistency in the conditions specified for our experimental and their computational work.

We have held teleconferences with Dr. Tony Pilon and Dr. Brian Smith from Lockheed Martin. Specifically, we have discussed how we can aid Dr. Smith's ONR project, "Improved V/STOL Phenomena Simulation." We also participated in the workshop for fixed wing STOVL research to promote technology exchanges organized by Dr. David Findlay, NAVAIR Aeromechanics Division (4.3.2) S&T lead and Dr. Jae Lee in April 2015.

8. Personnel supported

Principal investigator: Dennis K. McLaughlin
Co-investigator: Philip J. Morris

Graduate Students:

1) Nicholas Rudenko, MS candidate

2) Christopher Shoemaker, MS candidate.

3) Scott Hromisin, a PhD student who receives his funding from a SMART scholarship administered through AIR 4.3.2.1 of NAVAIR, Patuxent River, works part-time on this project.

4) Jonathan Zuk, MS candidate, who has been performing the computations while in full time employment in industry in Delaware. He has been receiving academic credit for the work he has been doing on this project.

9. **Publications** (resulting from this project):

Conference Papers

Rudenko, N.A., Hromisin, S.M. and McLaughlin, D.K., “Thermal Characterization of a Dual Impinging Jet Flow Field with a Heated Jet”, Presented at the AIAA Aviation Meeting, Washington, DC, June 2016

Myers, L.M., Rudenko, N., and McLaughlin, D.K., “Investigation on the Flow-Field of Two Parallel Round Jets Impinging Normal to a Flat Surface”, AIAA Paper No. 2016-1776, presented at the 54th AIAA Aerospace Sciences Meeting, San Diego, CA., January 2016.

Hromisin, S., Myers, L.M., McLaughlin, D.K. and Morris, P.J. “A Comparison of the Aeroacoustic Characteristics of Free and Impinging Jets with Deflected Seals Noise Reduction Technique”, AIAA Paper No. 2016-0526, presented at the 54th AIAA Aerospace Sciences Meeting, San Diego, CA., January 2016.

Hromisin, S., Rudenko, N., Myers, L. and McLaughlin, D.K. “Laser Doppler Velocimeter Measurements in the Ground Interaction Region of an Impinging Scale Model Jet,” in AHS 71st Annual Forum, Virginia Beach, VA. 2015.

Myers, L.M. and McLaughlin, D.K., “Outwash Measurements of a Dual Impinging Jet Scale Model,” AIAA 2015-1937, presented at the AIAA Sci-Tech Conference, Kissimmee, Florida, Jan, 2015.

Myers, L.M., Rudenko, N., and McLaughlin, D.K., “Experimental Study of the Environmental Flow-field of Two Impinging Model Scale Jets,” AHS 70th Annual Forum, Montreal, Quebec, Canada, 2014.

Myers, L.M., Kuo, C.W., and McLaughlin, D.K., “Far-Field Acoustic Measurements of Dual Impinging Scale Model Jets,” 20th AIAA/CEAS Aeroacoustics Conference, Atlanta, GA, 2014.

Other Publications

Rudenko, N.A., “Investigation of the Heat Transfer of two Jets Impinging Normal to a Flat Surface” MS Thesis, Penn State University, August, 2016.

Crowell, A. R. and L. M. Myers “Computational Analysis, Model Reduction, and Experimental Comparison of Model Scale Impinging Jets,” AIAA Paper No. 2016-0310, presented at the 54th AIAA Aerospace Sciences Meeting, San Diego, CA., January 2016

Zuk, J. “Development of a Transient Conduction Heat Transfer Computational Model to use with a Quasi-Steady CFD Analysis of a Heated Jet Flow Impinging on a Level Ground Plane”, Masters paper, Penn State University, June 2016

Myers, L.M., “Investigation of the Flow-field of two Parallel Round Jets Impinging Normal to a Flat Surface,” PhD Dissertation, Penn State University, August 2015.

Hromisin, S. M. “Laser Doppler Velocimetry Measurements of a Scale Model Supersonic Exhaust Jet Impinging on a Ground Plane,” M.S. Thesis, The Pennsylvania State University, Mechanical Engineering, 2015.

Karns, A., “Development of a Laser Doppler Velocimetry System for Supersonic Jet Turbulence Measurements,” The Pennsylvania State University, Aerospace Engineering M.S. Thesis, 2014.

10. Point of Contact in Navy

Our main Point of Contact on this grant is Dr. David Findlay of NAVAIR, Patuxent River, MD has held numerous telephone discussions with the project P.I. and also visited Penn State during his service as a Committee member on Leighton Myers doctoral committee. Dr. Judah Milgram, our Program Manager, has visited Penn State on two occasions during the past couple of years and at one meeting had an extensive review of our laboratory facilities. Copies of Conference papers and presentations have been sent to both Dr. Milgram and Dr. Findlay.

11. Acknowledgement/Disclaimer

This work was sponsored by the Office of Naval Research, ONR, under grant/contract number # N000141410830. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Office of Naval Research, or the U.S. government.

Section II: Project Metrics

Grant # N000141410830

Experimental Study of Impinging Jet Flow-Fields

Final Report for Period: Jun 15, 2014 – Jun 14, 2016

PI: Dennis K. McLaughlin
814-865-2560, dkm2@psu.edu
Co-PI: Philip J. Morris
The Pennsylvania State University

Date Prepared: July 27, 2016

ONR Technical Representative: Dr. Judah Milgram

Metrics

Number of faculty supported under this project during this reporting period: 2

Number of post-doctoral researchers supported under this project during this period: N/A

Number of graduate students supported under this project during this reporting period: 2

Number of undergraduate students supported under this project during this period: 1

Number of refereed publications during this reporting period for which at least 1/3 of the work was done under this effort: 0

Number of publications (all) during this reporting period; 7

Number of patents during this reporting period: 0

Number of M.S. students graduated during this reporting period: 2

Number of Ph.D. students graduated during this reporting period: 1

Awards received during this reporting period: N/A

Invited talks given: 0

Conferences at which presentations were given (not including invited talks above): 6

12. Financial information

Leighton Myers – SMART Scholarship, Fall 2010 through Spring 2015.

Leighton Myers – NAVAIR ILIR-14-010 "Investigation of Dual Impinging Jet In-Ground Effect Environment/Flow-Field through Model Scale Experiments."

Scott Hromisin - SMART Scholarship, Fall 2015 through present.

FY 2015-2016 FINAL Report	Total Budget	Obligated This Period	Obligated Cumulative	Expended This Period	Expended Cumulative	Grant/ Contract Period of Performance
6.1 (Basic Research Funding)	**$179,000**	**$179,000**	**$179,000**	**$179,000**	**$179,000**	**June 13, 2014- to June 12, 2016**
6.2 (Applied Research Funding)						
Total (if both 6.1 and 6.2 funding was used)						

13. Administrative notes and other items of interest

N/A

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13. SUPPLEMENTARY NOTES
The research was conducted in cooperation with Dr. Andrew Crowell of AIR 4.3.2.1 Branch at NAWC, Patuxent River, MD.

14. ABSTRACT
This project focused on experiments to improve the understanding and aid in the analysis of Short Take-Off and Vertical Landing (STOVL) vehicle aerodynamics during sea-based operations. The goal of the research was to conduct experiments to define the major features of complex dual impinging jet flow-fields and to guide numerical simulation developments and evaluate the accuracy of the predictions. The laboratory model consists of dual jets impinging on a large flat plane to simulate the jets that provide powered lift for STOVL aircraft. The nozzles are mounted in a simplified aircraft underside, or lift plate. A pitot pressure rake and a Laser Doppler Velocimeter (LDV) were used for mean and turbulence velocity surveys of the jet plumes and out-wash flow. The laboratory model included the addition of a jet heating together with a large number of thermocouples positioned at strategic positions throughout the apparatus. Measured temperature distributions were compared with those predicted by the coupled CFD- conjugate heat transfer calculations, in which the CFD computations were provided by the AIR 4.3.2.1 Branch at NAWC. Preliminary data comparisons indicate that the computational models have good accuracy with considerable opportunity for further development.

15. SUBJECT TERMS
Experiments on simplified models of STOVL powered lift; guide numerical simulation developments; unclassified

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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